Draft version February 5, 2008
Preprint typeset using LaTeX style emulateapj v. 11/26/04

FLUORINE ABUNDANCES IN PLANETARY NEBULAE

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Draft version February 5, 2008

ABSTRACT

We have determined fluorine abundances from the [F II] λ4789 and [F IV] λ4060 nebular emission lines for a sample of planetary nebulae (PNe). Our results show that fluorine is generally overabundant in PNe, thus providing new evidence for the synthesis of fluorine in asymptotic giant branch (AGB) stars. [F/O] is found to be positively correlated with the C/O abundance ratio, in agreement with the predictions of theoretical models of fluorine production in thermally pulsing AGB stars. A large enhancement of fluorine is observed in the Wolf-Rayet PN NGC 40, suggesting that high mass-loss rates probably favor the survival of fluorine.

Subject headings: ISM: abundances — planetary nebulae: general — line: identification

1. INTRODUCTION

The astrophysical origin of fluorine is still an unresolved issue. The element has only one stable, yet rather fragile, isotope ^{19}F. In stellar interiors it is readily annihilated by the most abundant elements hydrogen and helium, via reactions ^{19}F(p, α)^{16}O and ^{19}F(α, p)^{22}Ne, respectively. In order to explain the presence of F a mechanism is required that enables F to escape from the hot stellar interior after it is created. Three scenarios have been proposed as the potential sources of F: explosions of Type II supernovae (SNe), stellar winds of Wolf-Rayet (WR) stars, and the third dredge-up of asymptotic giant branch (AGB) stars. Woosley & Haxton (1988) show that inelastic scattering of neutrinos escaping from the collapsing core of a Type II SN by nuclei in the shell, often referred to as the ν-process, can convert ^{20}Ne into ^{19}F. In WR stars, ^{19}F is probably produced during the He-burning phase and then ejected into space by strong stellar winds before it is destroyed (Meynet & Arnould 2000). For AGB stars, Forestini et al. (1992) propose that ^{19}F is synthesized and then dredged up to the surface during the He-burning thermal pulses. The reaction chain for F production in WR and AGB stars is ^{14}N(α, γ)^{18}F(β^+)^{18}O(p, α)^{15}N(α, γ)^{19}F, where protons are liberated through ^{13}C(α, n)^{16}O followed by neutron captures ^{14}N(n, p)^{14}C. Based on a semi-analytic model, Renda et al. (2004) suggest that both WR and AGB stars are significant sources of F. To discriminate between the three possible scenarios of F production, accurate measurements of F abundances in these objects are needed.

Observations of F outside the solar system have been scarce. A pioneering work was carried out by Jorissen et al. (1992), who determined F abundances in red giants using infrared HF vibration-rotation transitions and found enhanced F in C-rich stars, providing evidence of F production in AGB stars. Their results were supported by observations of F V and F VI absorption lines in the far-UV spectra of hot post-AGB stars (Werner et al. 2005). On the other hand, Cunha et al. (2003) measured HF lines for a sample of nine red giants (RGs) in the Large Magellanic Cloud (LMC) and two RGs in the Galactic globular cluster ω Centauri. Very low F/O ratios were found for the two metal-poor ω Cen giants. Given that the cluster must have been significantly enriched by AGB evolution, as indicated by large enhancements of *s*-process elements observed in its member stars, they concluded that AGB stars are probably not the dominant source of F. To our knowledge, no observation of F in a WR star has been reported to date. The first measurement of interstellar F was obtained by Federman et al. (2005), who detected F I λ955 interstellar absorption in two sight lines towards the Cep OB2 association using the Far Ultraviolet Spectroscopic Explorer (*FUSE*). Their measurements yield no evidence of enhanced F abundances resulting from the ν-process in Type II SNe.

Planetary nebulae (PNe) are ejected from AGB stars and they therefore serve as a direct test bed for F production in AGB stars. Given its low condensation temperature, depletion of F onto dust grains is unlikely to be significant in PNe. Nevertheless, due to its intrinsic low abundance, F emission lines are difficult to measure in PN spectra. Based on uncertain measurements of the [F IV] λ4060 nebular line in two PNe, Aller & Czyzak (1983) claimed that the F abundance in PNe was consistent with the solar value. A definite measurement of the F abundance was presented by Liu (1998) for the high-excitation PN NGC 4361, indicating that F was overabundant in this metal-poor PN possibly belonging to the halo population.

In this paper we present F abundances for a sample of PNe and we examine the F production in AGB stars. In Section 2, we survey measurements of the [F II] λ4789 and the [F IV] λ4060 lines available from recently published high quality spectra. The derived abundances are presented in Section 3. A discussion follows in Section 4, and section 5 summarizes the results.

2. FLUORINE EMISSION LINES

Among the ionic species of fluorine, F$^+$ and F^{3+} are detectable in the optical via the [F II] ^{1}D$_2$–^{3}P$_2$ λ4789.48 and the [F IV] ^{1}D$_2$–^{3}P$_2$ λ4059.94 nebular lines, respectively. We have surveyed high signal-to-noise spectra published in the literature (see the last column of Ta-

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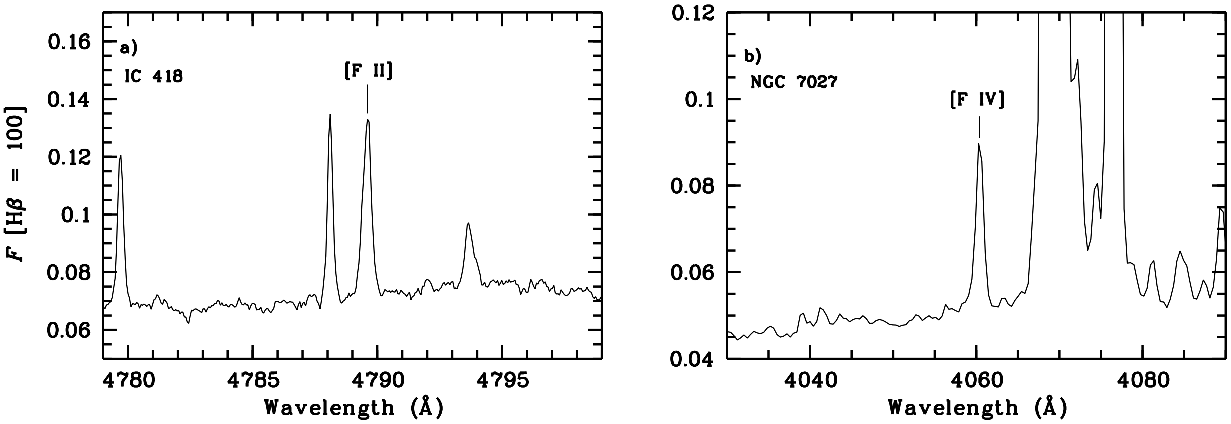

FIG. 1.— a) Spectrum of a low-excitation PN IC 418 showing the [F II] λ4789 line; b) Spectrum of a high-excitation PN NGC 7027 showing the [F IV] λ4060 line. Note that interstellar extinction has not been corrected for.

ble 1). Many of them are published recently by our own and other research groups, obtained in spectroscopic surveys aimed at detecting weak emission lines from heavy element ions.

PNe from which the [F II] λ4789 line or the [F IV] λ4060 line have been detected are listed in Table 1. The fact that all PNe where the [F II] line is detectable are low-excitation PNe and all PNe from which the [F IV] has been detected are high-excitation objects strengthens the confidence in our line identifications. Fig. 1 plots the spectra of two PNe, one of low-excitation and another of high-excitation, around the wavelengths of the [F II] line and the [F IV] line, respectively. The excitation class (E.C.) and the dereddened intensities of the [F II] λ4789 and the [F IV] λ4060 line, relative to that of Hβ, are listed respectively in Cols. 2, 3, and 4 of Tables 1. Typical intensities of the two fluorine lines relative to Hβ are of the order of 10^{-4}.

Baldwin et al. (2000) report detection of the [F II] λ4789 line from the Orion Nebula, albeit with a low signal-to-noise ratio. A feature at the right wavelength has also been detected by Peimbert et al. (2004) in the low-excitation PN NGC 5315, but identified by them as N II. Given that the feature does not appear in high-excitation PNe, we regard this as a mis-identification. The detection of this line is very uncertain in the low-excitation PN IC 2501 because of severe contamination at this wavelength by scattered light from Hβ.

An unidentified weak feature has been detected in the echelle spectrum of IC 418 at 4869 Å (cf. Sharpee et al. 2003). We identify it as the [F II] $^1D_2$–$^3P_1$ transition at 4869.02 Å. Given the fact that the [F II] $\lambda\lambda$4789, 4869 lines arise from the same upper level, the λ4789/λ4869 intensity ratio depends only on their spontaneous transition probabilities, and not on the nebular physical conditions. For IC 418, the measurements yield a λ4789/λ4869 intensity ratio of 5.2. In the spectrum of the bright high-excitation PN NGC 7027, we have detected the [F IV] $^1D_2$–$^3P_1$ transition at 3996.96 Å (cf. Zhang et al 2005). The measurements yield an intensity ratio $I(4060)/I(3997) = 3.6$. Note that under the assumption of LS-coupling, the intensity ratio of the $^1D_2$ – $^3P_2$ to $^1D_2$ – $^3P_1$ transitions is simply given by $3 \times [\lambda(^1D_2 - {}^3P_1)/\lambda(^1D_2 - {}^3P_2)]^3$. This relation predicts an intensity ratio of 3.2 and 2.8 for [F II] λ4789/λ4869 and [F IV] λ4060/λ3997, respectively. On the other hand, in the well studied case of the much stronger [O III] $\lambda\lambda$4959,5007 nebular lines, based on high quality observations, Mathis & Liu (1999) demonstrate that $\lambda5007/\lambda4959 = 3.00 \pm 0.01$, significantly higher than the value of 2.88 predicted by the above theoretical relation under LS-coupling. Storey & Zeippen (2000) have recently recalculated intensity ratios of the $^1D_2$ – $^3P_2$ to $^1D_2$ – $^3P_1$ transitions for carbon-like and oxygen-like ions, taking into account the effects of the relativistic corrections for the magnetic dipole operators. For [O III], they find that the λ5007/λ4959 ratio increases from the LS-coupling value 2.88 to 2.98; the latter is in excellent agreement with the measurement of Mathis & Liu (1999). For [F II] and [F IV], the corresponding line ratios obtained by Storey & Zeippen (2000) are 3.12 and 2.90, respectively. Considering the uncertainties in measuring the extremely faint [F II] and [F IV] lines, especially the weaker [F II] λ4869 line, which falls very close to the strong Hβ and suffers from severe contamination by scattered light from Hβ, the discrepancies between the observations and theory, i.e. 5.2 versus 3.12 in the case of [F II] in IC 418, and 3.6 versus 2.90 in the case of [F IV] in NGC 7027, are probably insignificant.

Finally, we note that in the infrared, the [F IV] 25.8μm and 44.2μm fine-structure lines, analogues of the [O III] 51.8μm and 88.3μm lines, have intensities comparable to the optical [F IV] $\lambda\lambda$3996, 4060 lines, and are hence good candidates to search for fluorine in PNe, especially in those that suffer from large dust extinction in the optical.

3. FLUORINE ABUNDANCE DETERMINATIONS

F^+/H^+ and F^{3+}/H^+ ionic abundances have been derived from the observed intensities of the [F II] and [F IV] lines, respectively, following standard procedures. Multi-level collisional-radiative models were constructed for F^+ and F^{3+}, using collision strengths from Butler & Zeippen (1994) and Lennon & Burke (1994), and radiative transition probabilities from Baluja & Zeippen (1988) and Fisher & Saha (1985), respectively. When calculating F^+ ionic abundances, we have adopted electron densities derived from the [S II] λ6731/λ6716 ratio and temperatures deduced from the [N II] nebular-to-auroral line ratio. For F^{3+}, densities derived from the [Ar IV] λ4740/λ4711 ratio and temperatures obtained from the [O III] nebular-to-auroral line ratio were used. Given the relatively high critical densities ($> 10^6$ cm^{-3}) of the [F II] λ4789 and [F IV] λ4060 lines, the abundances are essen-

TABLE 1
Measurements of fluorine in nebulae[a].

Source	E.C.[b]	$I([\mathrm{F\ II}]_{4789})$[c]	F^+/H^+	O^+/H^+	F/O[d]	C/O	O/H	Ref.
IC 418	1	2.72(−4)	4.34(−8)	1.70(−4)	2.55(−4)	1.8	2.90(−4)	S04
IC 2501	3	1.70(−5):	3.38(−9):	8.25(−5)	4.09(−5):	1.2	5.13(−4)	W05a
NGC 40	1	6.60(−4)	2.95(−7)	4.83(−4)	6.10(−4)	1.4	4.90(−4)	L04
NGC 5315	2	4.40(−5)	6.45(−9)	4.17(−5)	1.54(−4)	0.95	7.41(−4)	P04
Orion	···	5.37(−5)	9.01(−9)	7.94(−5)	1.13(−4)	0.58	4.47(−4)	B00
Source	**E.C.[b]**	$I([\mathrm{F\ IV}]_{4060})$[c]	F^{3+}/H^+	Ne^{3+}/H^+	F/O[d]	C/O	O/H	Ref.
IC 2003	10	1.69(−3)	3.49(−8)	4.19(−5)	1.65(−4)	0.93	2.75(−4)	W05b
NGC 2022	12	1.84(−3)	2.31(−8)	4.47(−5)	7.82(−5)	0.46	4.57(−4)	T03
NGC 2440	10	2.17(−4)	3.28(−9)	5.29(−5)	1.26(−5)	0.90	4.40(−4)	W05a
NGC 3242	9	6.48(−5)	1.75(−9)	9.18(−6):	4.46(−5):	0.41	3.31(−4)	T03
NGC 3918	9	3.75(−4)	7.84(−9)	5.95(−5)	1.69(−5)	0.60	7.24(−4)	T03
NGC 4361	12+	3.10(−3)	2.57(−8)	2.54(−5)	6.82(−4)	2.0	6.61(−5)	L98
NGC 6302	10	6.77(−4)	4.99(−9)	2.37(−5)	6.35(−5)	0.30	2.51(−4)	T03
NGC 7027	11	9.10(−4)	1.71(−8)	4.19(−5)	1.04(−4)	2.7	4.57(−4)	Z05
NGC 7662	10	8.50(−4)	1.47(−8)	4.30(−5)	5.93(−5)	1.4	3.31(−4)	L04

References. — [B00] Baldwin et al. (2000); [L98] Liu (1998); [L04] Liu et al. (2004); [P04] Peimbert et al. (2004); [S04] Sharpee et al. (2003); [T03] Tsamis et al. (2003); [W05a] Williams et al. (2005); [W05b] Wesson et al. (2005); [Z05] Zhang et al (2005).

[a]Here $a(-b) = a \times 10^{-b}$; [b]From Gurzadyan (1997); [c]Corrected for reddening, and on a scale where $\mathrm{H}\beta = 1$; [d]The solar F/O ratio is 5.89(−5) (Lodders 2003).

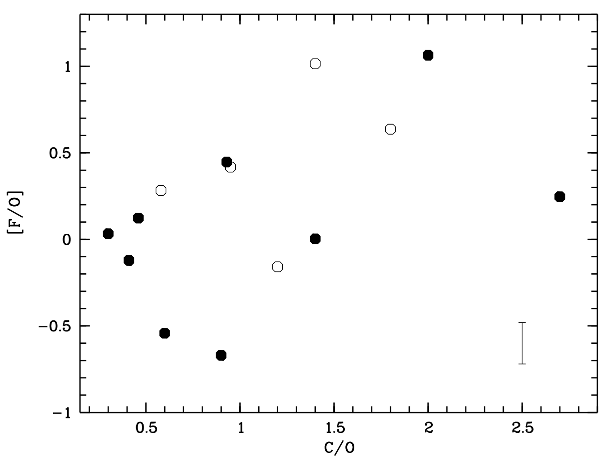

Fig. 2.— [F/O] versus C/O. Open and filled circles denote low- and high-excitation PNe, respectively. A correlation between the two quantities is apparent. The error bar on the lower right indicates typical uncertainties of [F/O].

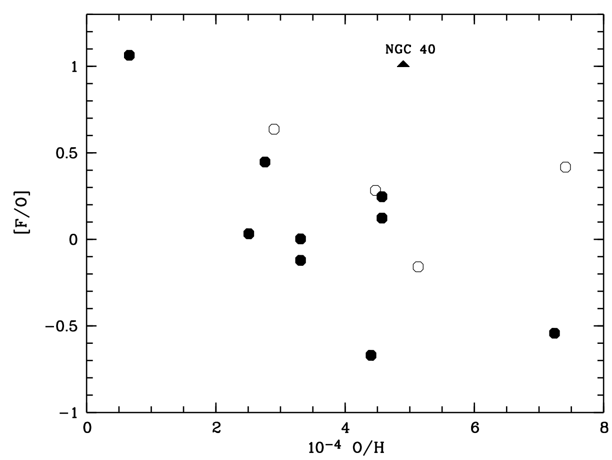

Fig. 3.— [F/O] versus O/H. Open circles and filled circles denote low- and high-excitation PNe, respectively. With the exception of NGC 40 (represented by a filled triangle), an anti-correlation between F/O and O/H is observed amongst other PNe.

tially independent of the adopted electron densities. For NGC 4361, we have adopted the F^{3+}/H^+ ratio of Liu (1998), obtained using the same atomic data set. The results are presented in Table 1.

To convert ionic abundance ratios to those of total elemental abundances, ionization corrections need to be made for unseen ions. Given that O^+ and Ne^{3+} have ionization potentials comparable to F^+ and F^{3+}, respectively, we assume that $F/O = F^+/O^+$ and $F/O = (F^{3+}/Ne^{3+})(Ne/O)$, for low- and high-excitation PNe, respectively. Ionic and elemental abundances of Ne, O and C adopted in our analysis were taken from the literature. Table 1 summarizes the abundances. Typical uncertainties in the F/O ratios are about 12 per cent.

4. DISCUSSION

The most recent measurement of the solar F/O abundance ratio yields $F/O = 5.89\times10^{-5}$ (Lodders 2003). Table 1 shows that most PNe exhibit F overabundances. The sample yields an average value [F/O]=0.3. Our measurements thus provide further evidence in support of Jorissen et al. (1992) who suggest that AGB stars can be a significant source of F production.

According to the AGB evolution models of Jorissen et al. (1992), fluorine is synthesized in the He intershell and then dredged up to the surface during the thermal pulses. During this process, He is converted into ^{12}C via partial He-burning in the intershell and then transported to the stellar surface along with F. The scenario thus predicts a positive correlation between the [F/O] abundance enhancement and the C/O ratio. Such a correlation is indeed observed in red giants (Jorissen et al. 1992) and in our current sample of PNe. In Fig. 2, we plot observed [F/O] versus C/O ratio for the sample. It is clear that [F/O] increases with increasing C/O ratio, which strongly suggests that F is indeed produced in He-burning environments of thermally pulsing AGB stars. Fig. 2 also shows

that there is no systematic difference between the F abundances deduced for low- and high-excitation PNe in our sample, suggesting that the ionization correction formulae adopted in our analysis are probably reliable.

No PN in our sample shows [F/O] overabundances as much as 30 times solar, as found by Jorissen et al. (1992) in giant stars. The highest [F/O] value observed in our sample is in the halo PN NGC 4361, which yields a F/O ratio 12 times solar. Lugaro et al. (2004) present new calculations of F yields in AGB stars. Their models fail to match the very high F abundances found by Jorissen et al. (1992). A comparison with Fig. 3 of Lugaro et al. (2004) shows that the [F/O] and C/O abundance ratios derived here for the current sample of PNe are in good agreement with the predictions of their $3\,M_{\odot}$ and $Z = 0.02$ model. The very high F abundances observed in some red giants thus remain a puzzle.

A large F enhancement of 10 times solar is observed in NGC 40, a PN ionized by a WC8 central star (Smith 1969; Crowther et al. 1970). The large enhancement is probably a consequence of the strong stellar winds from its progenitor star, leading to a larger amount of the synthesized F being ejected into space. It is possible that WR PNe play an important role in F production. Further spectroscopy of additional WR PNe is however required to verify this possibility.

Fig. 3 presents [F/O] versus O/H for the sample. Excluding the WR PN NGC 40, a negative correlation is seen, indicating that the dredge-up process that produces F is more efficient in a metal-poor environment. The result is in accord with the predictions of the dredge-up models (e.g. Boothroyd & Sackmann 1988) and the fact that more carbon stars are observed in metal-poor galaxies (Groenewegen 2004). NGC 40 does not follow this general trend, however it is consistent with the idea that strong stellar winds may have dramatically enhanced F in this nebula (see above).

It has been found that *s*-elements are generally overabundant in PNe (Williams et al. 2005), indicating that AGB stars experience strong slow neutron capture process. The origin of the neutrons, however, is much debated (see Busso, Gallino & Wasserburg 1999, for a review). Two possible sources have been proposed, ^{13}C(α, n)^{16}O and ^{22}Ne(α, n)^{25}Mg. If the later process dominates, then F is unlikely to survive in the He-intershell since the reaction rate of ^{19}F(α, n)^{22}Ne is much higher than that of ^{22}Ne(α, n)^{25}Mg (see Jorissen et al. 1992, for a detailed discussion). Consequently, our finding that F is generally enhanced in PNe rules out reaction ^{22}Ne(α, n)^{25}Mg as the main process of neutron production.

In this paper, we have also presented, for the first time, the F abundance for an H II region, the Orion Nebula (see Table 1). The value is about two times higher than those found for K–M dwarfs in the Orion Nebula Cluster (Cunha & Smith 2005). The significance of the finding is however questionable, given the considerable uncertainties in the line measurements – according to Baldwin et al. (2000), the extremely faint [F II] λ4789 nebular line has a signal-to-noise of only 5.3. Further observation of improved sensitivity should be helpful.

5. CONCLUSIONS

We have obtained measurements of the [F II] λ4789 and [F IV] λ4060 nebular emission lines from the recent literature for a sample of PNe. The lines are detectable in low- and high-excitation nebulae, respectively. From the measurements, abundances of fluorine are derived. Our results show that fluorine is overabundant in PNe compared to the solar value, suggesting that thermally pulsing AGB stars may play an important role in the production of the element. The result is further corroborated by the positive correlation observed between the derived [F/O] and C/O. Given that the WR PN NGC 40 shows a high F/O ratio, we infer that PNe with a WR central star are probably significant fluorine producers. Additional observations are required to verify this point.

We thank the anonymous referee for useful comments. YZ deeply appreciates R. Williams' hospitality during the year he worked in STScI. The work is partly supported by NNSFC grant #10325312.

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